Built-in Jitter Measurement Circuit For Voltage-Controlled Oscillator And Phase-Locked Loop

FIELD OF THE INVENTION

This invention relates to a built-in jitter measurement circuit

5 for a voltage-controlled oscillator (VCO) and a phase-locked loop

(PLL), wherein a divider is utilized for outputting the increasing

jitter of the signal to be measured such that the jitter of the original

un-divided signal is determined by some derivations.

BACKGROUND OF THE INVENTION

10 A voltage-controlled oscillator (VCO) and a

phase-locked loop (PLL) are commonly used components

in many circuit designs. Jitter of the output clock signal in

a VCO or a PLL determine the quality even the

performance of the output signal. Therefore jitter

15 measurement in a VCO and a PLL becomes indispensable

in the field of circuit design.

As a result of the rapid advancement of VLSI

technology, Frequently, a SoC (System on A Chip) has an

embedded PLL. However, there are many restrictions posed when external measuring equipment measures a built-in PLL. Such restrictions include noise from measuring environment and package pins, bandwidth limitation of the external measuring equipment and lack of input and output interface for built-in PLL to external. Compare with prior art methods measuring by external equipment, an internal measuring circuit has advantages such as low cost, faster measuring, better precision, less restriction on measuring capacity, and ability to perform at-speed testing.

Jitter is often less than several hundred pico seconds in many cases. Conventionally, internal measurement technologies are usually implemented by analog designs, which are complicated and expensive.

LogicVision Inc. utilizes components including delay-lines for adjusting delays, flip-flops and counters for counting timing intervals, and then combining with statistics method for calculating jitter. Nonetheless, its

precision and accuracy are limited to the resolution of the delay-lines and the setup time of the flip-flops.

Credence utilizes built-in clock generators for generating clocks of predefined periods. A signal to be measured is used for triggering the generated clocks. First cycle trigger the first generated clock and second cycle trigger the second generated clock. After the phase of the first generated clock matches the phase of the second generated clock, the period of the signal to be measured is determined by the number of cycles required for phase matching. By measuring the periods of the signal repeatedly, the jitter of the signal is determined combined with statistics method. The internal clock generators and matching decision devices used in such method restrict precision and accuracy of jitter measurement. Such method also requires extra device for performing statistics calculation and results in larger circuit area.

Precision level of jitter measurement taken by aforementioned methods only reaches several hundred

pico seconds. Antonio H. Chan and Gordon W. Roberts proposed a paper titled "A Synthesizable, Fast and High-resolution Timing Measurement Device Using a Component-invariant Vernier Delay Line" in the International Test Conference, 2001. Chan and Roberts applied a differential method for overcoming the precision restriction caused by minimum delay of a component. However, the extra design cost grows exponentially with improved precision, also, the differential values of components will shift when implemented in different manufacturing process and result in undetermined precision and undesirable accuracy.

SUMMARY OF THE INVENTION

The present invention provides a built-in jitter measurement circuit for a voltage-controlled oscillator (VCO) and a phase-locked loop (PLL) in a SoC for eliminating the need of external high-end tester, the interference from noise of environment, noise of output and input pins in measurement.

The main objective of the present invention is to provide a built-in jitter measurement circuit, wherein period jitter and long-term jitter are determined by statistics calculation performed by the circuit and as a result eliminating the needs for massive data output and a process for complicated statistical analysis of the data.

Another objective of the present invention is to provide a built-in jitter measurement circuit, wherein a test integration method and a test subtraction method are applied for increasing precision and accuracy of jitter measurement.

Another objective of the present invention is to provide a built-in jitter measurement circuit, wherein an all digital standard cell-based design is adapted for increasing reliability and noise immunity. Such design avoids difficulties faced in analog designed and is suited for different manufacturing processes.

Another objective of the present invention is to provide a built-in jitter measurement circuit, wherein the

measurement circuit is embedded with DfT (Design for Test) for ensuring the test quality.

Another objective of the present invention is to provide a built-in jitter measurement circuit, wherein the circuit is applicable to a core-based self test circuit in a SoC.

Another objective of the present invention is to provide a built-in jitter measurement circuit, wherein measuring the divided and jitter increased signal of the output clock of the opened-loop circuit and accordingly long-term jitter of the output clock of the opened-loop circuit can be determined.

Another objective of the present invention is to provide a built-in jitter measurement circuit, wherein jitter measured from several measurements are calculated by extrapolation for recovering the period jitter and eliminating the error caused in measurement.

Another objective of the present invention is to provide a built-in jitter measurement circuit, by

measuring the bandwidth of a closed-loop circuit, accordingly, jitter of output clock of the closed-loop, which is jitter defined in a PLL, is measured by correlating the measured bandwidth and the jitter from extrapolation.

Another objective of the present invention is to provide a built-in jitter measurement circuit, wherein TDC comprising latch chain is adapted for measuring periods. The present invention is characterized by being able to perform operating modes of HOLD, CLEAR and RUN in the same cycle, and a fact that values represented by digital output are in proportion to the time of the periods.

Another objective of the present invention is to provide a built-in jitter measurement circuit, where the circuit performs statistical calculation. The outputs of the TDC and the square of the outputs are added up for determining the jitter of the signal.

Another objective of the present invention is to provide a built-in jitter measurement circuit, equalization

encoding is applied for linearizing the output of the TDC and balancing the difference between rising-time and falling-time of the signal in a standard cell in the latch chains so that measurement errors are reduced and

5   enhancing the precision.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a Gaussian distribution diagram of periodical signal jitter;

FIG. 2 is a curve diagram illustrating measurement of

10   an opened-loop and a closed-loop jitter;

FIG. 3 is a diagram illustrating waveform correlation between signal to be measured x(t) and divided signal to be measured y(t);

FIG. 4a is a schematic curve diagram illustrating the

15   jitter measurement method used according to the present invention;

FIG. 4b is a curve diagram illustrating frequency response of a PLL;

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FIG. 5 is a design block diagram illustrating the jitter measurement circuit;

FIG. 6a is a design block diagram illustrating a time to digital converter (TDC);

5 FIG. 6b is a design block diagram illustrating a test circuit having multiplexers and D flip-flops;

FIG.7 is a timing diagram illustrating the TDC;

FIG. 8 is a data diagram illustrating comparison between linear encoding and equalization encoding;

10 FIG. 9 is a data diagram illustrating simulation results of different input periods;

FIG. 10 is data diagram illustrating simulation results of different divided settings; and

FIG. 11 is a data diagram illustrating simulation 15 results of different input jitter.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

(I) Jitter Measurement Scheme

FIG. 1 describes a Gaussian distribution of jitter for periodical signal, where t is a random variable of signal's period, p(t) is a probability density and σ_x is the standard deviation. FIG. 2 describes measurement results of long-term jitter of an opened-loop and a closed-loop circuits, where T is time, $\sigma_L(T)$ is a long-term jitter for T, κ is a constant coefficient, and τ_L is the loop bandwidth of a closed-loop circuit. For an opened-loop signal, if its period is T and period jitter is σ_P, then the n-periods long-term jitter for it is $\sigma_L(nT) = \sqrt{n} * \sigma_P$. However, the long-term jitter for a closed-loop circuit is expected to be stabilized as $\sigma_L(\tau_L) = \sqrt{\dfrac{\tau_L}{T}} * \sigma_P$ when the measurement time is longer than τ_L. Such stabilized long-term jitter measurement of a closed-loop circuit is considered as the jitter measurement of a PLL.

Based on the conclusions above, as shown in the FIG. 3, if a periodic signal to be measured is x(t), period of each cycle is x_1, x_2, x_3 ..., signal divided by n is y(t), each period set is y_1, y_2, y_3 ..., and then equations are described

as follows:

$$y_1 = x_1 + x_2 + ... + x_n$$

$$y_2 = x_{n+1} + x_{n+2} + ... + x_{2n}$$

$$...$$

$$y_k = x_{(k-1)n+1} + x_{(k-1)n+2} + ... + x_{kn}$$

$$...$$

Also, new random variables are defined as follows:

$$S_1 = \{x_1, x_{n+1}, x_{2n+1}, ...\}$$

$$S_2 = \{x_2, x_{n+2}, x_{2n+2}, ...\}$$

$$S_3 = \{x_3, x_{n+3}, x_{2n+3}, ...\}$$

$$...$$

$$Y = \{y_1, y_2, y_3, ...\}$$

5   As a result, $Y = S_1 + S_2 + S_3 + ... + S_n$. Because S_k (k=1,2,...,n) are random variables independent of each other for a opened-loop PLL or VCO, therefore equations are described as follows:

$$M_Y = M_{S_1} + M_{S_2} + ... + M_{S_n}$$

$$\sigma_Y^2 = \sigma_{S_1}^2 + \sigma_{S_2}^2 + ... + \sigma_{S_n}^2$$

10   For random variables, $M_{s1} = M_{s2} = ... = M_{sn} = M_X$ and

$\sigma_{s1} = \sigma_{s2} = \ldots = \sigma_{sn} = \sigma_X$, accordingly the equation is reduced to:

$$M_Y = nM_X$$
$$\sigma_Y^2 = n\sigma_X^2$$

The jitter of the signal to be measured $x(t)$ is too low

5   to be accurately measured. On the other hand, the jitter of the signal to be measured $y(t)$ is not. So by measuring the jitter of the signal divided by n, $y(t)$, long-term jitter of signal $x(t)$ with n times period is attained. Also, it follows that the period jitter (σ_X) of $x(t)$ can also be attained. In

10   addition, If there are errors caused by frequency divider or other factors, a new random variable $E = \{e_1, e_2, e_3, \ldots\}$ is defined to represent the errors. Accordingly, equations are represented as follows:

$$Y' = \{y_1 + e_1, y_2 + e_2, y_3 + e_3, \ldots\}$$
$$M_{Y'} = nM_X + M_E$$
$$\sigma_{Y'}^2 = n\sigma_X^2 + \sigma_E^2 \qquad \text{(EQU-1)}$$

15   According to the equations, calibration can be performed as long as measurement data by setting

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different n is provided. Thus errors are corrected and measurement accuracy is enhanced. In other words, the long-term jitter of the original signal can be attained by measuring the period jitter of the signal having frequency divided according to the conclusion reached above. As J_1, J_2, J_3 and the curve linked in between shown in FIG. 4a, opened-loop curve is attained after measurement errors are calibrated by setting different n and extrapolation is conducted. Then as shown in the FIG. 4b, τ_L is the inverse of the measurement of the bandwidth of the PLL when input frequency is set in increments. Apply the τ_L in the FIG. 4a. The jitter of PLL J_{PLL} (short for stabilized value of long-term jitter of a closed-loop PLL) is thus attained at the intersection of opened-loop curve and the τ_L curve.

(II) An implementation of embedded jitter measurement circuit

An embedded jitter measurement circuit is described as the following. The circuit is provided for measuring signal after frequency dividing and is based on the

equations as follows:

$$M_y = \sum_{i=1}^{N} y_i / N$$

$$\sigma_y^2 = (\sum_{i=1}^{N} y_i^2 / N) - M_y^2$$

The divisor N in the equations above can be set as 2^7 = 128 to reduce the hardware area.

5   As shown in FIG. 5, a block diagram of the embedded circuit is described which includes a 1/n Divider 1, a state controller 2, a variance calculator 3, a mean calculator 4, a encoder and counter 5, and a time to digital converter (TDC) 6.

10   The circuit operates as following steps. The divider 1 divides an input signal and outputs a signal, which is easier to be measured than the original signal. The period of the divided signal is converted into digital values by TDC 6, encoder and counter 5. The digital values are put

15 into calculation by the variance calculator 3 and the mean calculator 4 for calculating the mean of period and jitter value of the divided signal. The jitter value calculated

represents the long-term jitter of the original signal with a period of n times. In addition, because the n can be sets to different values, an equation 11 can be applied for calculating the period jitter of the original signal.

5   The design of the TDC 6 is shown in the FIG. 6a. The TDC 6 includes a latch chain 61, a counter 62, an encoder 63 and a set of D flip-flops 64. Digital output values represent the time when the input signal during high level. By appropriate timing setting, the TDC performs

10   operating modes of HOLD, RUN and CLEAR in a single synchronous cycle according to the present invention. When signal enable goes to low level, the latch chain 61 stop to transmit signal, the operating mode is in HOLD mode. When the signal enable goes to high level and the

15   reset signal goes to low level, the signal will be inversed at a NOR-gate and circulate in the latch chain 61, the operating mode is in RUN mode. When the signal enable goes to high level and the reset signal goes to high level, the latch chain continues to circulate digital value zero

20   until the whole loop is stored with digital value zero, the

operation mode is in CLEAR mode. Because rise delay time and the fall delay time may not be the same in the latch chain 61, equalization encoding is used in the present invention for enabling a linear curve between the TDC output and the period of the original signal.

Refer to FIG. 6b, a DfT (Design for Test) circuit is embedded in the measurement circuit. Before implement with full scan design, the fault coverage achieved is only 63%. If only full scan is implemented, then the fault coverage can be improved as 82%. When the circuit further comprises a multiplexer 65 and a D flip-flop 66 for correcting random output of latch chain, the fault coverage is increased as 91% and the test coverage is increased as 100%.

To realize the function of TDC 6 described previously, the timing design implemented in the embodiment according to the present invention is as shown in FIG. 7. A first clock clk is delayed for a time t_d and results in a second clock clkd. The clkd is used for

assisting to the timing control of a reset signal rst and control signal enable. When the first clock goes to high level, the operation mode is in the RUN mode. When the first clock goes to low level, the operation mode is in a HOLD mode. When the reset signal rst goes to rising edge, the value of the encoder and counter is latched. It follows that the latch chain is cleared to zero and the operation mode enters into CLEAR mode before the following first clock clk goes to high level.

The present invention is characterized by being able to perform operating modes of HOLD, CLEAR and RUN in the same cycle, and the digital signal measured is in proportion to the time duration of high level. Consequentially, the width of high (the time duration that signal equals to 1) must have to form a stable duty cycles, thus the measurement result is in proportion to the period. The divider used in the present invention provides a stable duty cycle signal to the TDC when n>=2. The present invention provides a continuous measuring of period for each clock generated without waiting.

Equalization encoding is another concept proposed in the present invention for eliminating measurement errors. Such measurement errors are caused by the difference between the rising-time and the falling-time in each

5   standard cell. Such measurement errors also result in depicted errors of the TDC output. An example is described as below. As shown in the FIG. 8, the first column represents steps the signal in the latch chain moved, and the second column represents the actual delay

10   time depicted. It is noted that the difference between the beginning digital values is low due to the delay time is short, and the difference between the following digital values is high due to the delay time is long. If a traditional encoding (T.E.) is implemented in the example, the same

15   steps result in the same code. Thus, based on the T.E., depicted time represented by the digital values output from the TDC results in significant errors. The third column is the T.E. The fourth column is the depicted delay indicated by each code. The fifth column is the error

20   percentage of the difference of indicated time and the

actual time, and divided by the average time step, wherein

the average time step is 2.4 ns/8=0.3 ns.   :

$$Error = \frac{Encoded\ Delay - Actual\ Delay}{Averge\ Time\ Step} \times 100\%$$

The equalization encoding proposed by the present invention is a method for selecting a code, which is the closest value of the output digital value output from the TDC. The delays between adjacent codes almost equal to each other hence the method is called equalization code. Such method can be designed in the register transfer level before the synthesis. The area and speed achieved by the circuit mentioned above is similar to the area and speed achieved by the circuit synthesized by T.E. The sixth column in the FIG. 8 is the equalization encoding (E.E.) proposed in the present invention. The seventh column is the depicted time indicated. The eighth column is the accumulated delay time based on the E.E. according to the present invention. According to data in the eighth column, it is noted that the E.E. of present invention significantly eliminates the errors compare to the T.E.

(III) Simulation result of the embodiment of the present invention

Simulation result of the embodiment is described in

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the FIG. 9, Fig. 10 and Fig. 11 for a TSMC 0.25um design, wherein T is the period of an input signal, σ_x is the jitter of the input signal, n is the divisor applied in the input divider, and mean and var2 are the digital output values

5 from the embedded test circuit. Jitter σ_m and the measurement errors can be attained from the equation as follows:

$$\sigma_m = \sqrt{n \times var2} \times \frac{T}{mean}$$

$$error = \frac{\sigma_m - \sigma_x}{\sigma_x} \times 100\%$$

10 For signal with different input period, if n is fixed as 64, and input signal jitter is fixed as 300 ps, then the measurement error is less than 4,23%. The minimum of an input period is limited by three factors. The first is the maximum of the operating speed of the divider, second is

15 the maximum operating speed of the TDC, the third is the jitter can not too large compared to the signal average period. The last row shown in the FIG. 9 is in violation of the third factor mentioned above. Those factors can be

expressed in the equations as follows:

$T \geq 0.85$ ns

$nT \geq 30$ ns

$T \geq 10\sigma_x$ \qquad (If x_i is within $\pm 5\sigma_x$)

5   The digital width of TDC determine the maximum of the input period. For a 12 bit design, if the signal period is lower than $0.3 \times 20 \times 212$(ns) $= 24.6$(us), the error is limited within 5%. Such a range of input signal is subject to the design of a circuit.

10   Fig. 10 and FIG. 11 are simulation results of output jitter by different settings of the divisor and the input jitter. Most of the results indicate that the error is small. It is observed that, for signal having different σ_x, the n has to follow the equation below to limit the error within 5%.

15    $0.3 \times \sqrt{20} < \sqrt{n}\sigma_x < 0.3 \times 2^7 \times 1/5$

$\Rightarrow 1.34\text{ns} < \sqrt{n}\sigma_x < 7.68\text{ns}$

     Errors observed in the first row in the FIG. 10 and

the first and the second row in the FIG. 11 are significant due to the fact that $\sqrt{n}\sigma_x$ is too small. The last row in the FIG. 10 fails to perform the simulation because the $\sqrt{n}\sigma_x$ is too large.

5   In conclusion, given the period and jitter of a signal to be measured may be different, as long as an appropriate n is selected to introduce in the equations above, simulation results can be attained accurately. In example of the simulation result by the last row in the FIG. 11, the

10   input clock is 1.5 ns and jitter is only 40 ps, for n=1024, the error is only 2%.

Based on the accompanying drawings, a practical embodiment of a built-in jitter measurement circuit for a voltage-controlled oscillator and a phase-locked loop

15   according to the present invention have been described. However, the present invention is not limited to the illustrated method. It will be apparent to those skilled in the art that various changes, improvements, and modifications can be made thereto without departing from

the spirit or scope of the invention.